Optimizing thermal and mechanical performance in PCBs

Engineers are always striving to make a lighter, faster and stronger PCB. In order to achieve their designs, engineers must turn to alternative materials to enhance their designs. There are many materials that allow for thermal, coefficient of thermal expansion (CTE) and rigidity. Many times if a material enables an engineer to have CTE they will have to sacrifice thermal. Currently carbon composite laminates are being used in order to achieve an ideal PCB with thermal, CTE and rigidity with almost no weight premiums.

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Introduction

Printed circuit boards (PCBs) are a key structural and electrical component of all electronics. The primary functions of PCBs are to provide an electrical interconnect for the components, to provide mechanical support for the components and to provide a safe working environment for the components. If an engineer were to design an ideal PCB it would have the capabilities it normally possess, but it would also further enhance the PCB to be thermally conductive (remove heat), provide CTE control to support flip chip or wafer level packages (WLP), have a low weigh structure for mobile applications, support mixed packages, and maintain its integrity at higher temperatures. Many different solutions have been used in the past, such as heavy metal cores or mechanical stiffeners, to solve some of these issues, but rarely have they solved all of the challenges. Currently carbon composite laminates are being used to tackle the PCB challenges of today.

PCBs have evolved a great deal from the past. The speed and processing that was required in the past has multiplied exponentially and will grow even more as technology develops. PCBs are facing many challenges such-as thermal fatigue, coefficient of thermal expansion (CTE) mismatch, solder joint stress, shock and vibration issues and high oven temperature processing issues.

Today's materials & their limitations

Table 1 displays the properties of the dielectric materials that are used to make PCBs. The materials have low Dk, low loss and high speed signal capability but do not have any thermal, limited CTE or limited rigidity capabilities to further enhance the PCB. Thus engineers have turned to alternative or additional thermal, CTE control and mechanical stiffeners. When engineers turn to alternate materials they only obtain one benefit while sacrificing in other areas. For example, using heavy copper allows for thermal, but the engineer must sacrifice weight and CTE. In order to use the heavy copper solution effectively and counterbalance the CTE affect of the material, the material must be placed deep within the center of the PCB. Thick metals also have their limitation in drilling applications. The material does not have the capability to be processed on high density

Table 1. Properties of dielectric materials used to make PCBs.

Dielectric Material	Thermal Conductivity (W/m.K)	CTE (ppm/°C)	Tensile Modulus (Msi)	Density (g/cc)
E-Glass Fiber	0.3 to 0.4	XY:5/6	10 to 12	2.54
FR-4/E-glass	0.3 to 0.4	XY:16/20, Z:60	3.5 to 4.5	1.6 - 1.8
Polyimide/E-glass	0.2 to 0.4	XY:15/19, Z:55	3.5 to 4.5	1.5 - 1.7
Non Woven Aramide/Epoxy	0.2 to 0.3	XY: 9/12, Z:120	2 to 2.1	1.25 - 1.3
PTFE Ceramic (RO3000)	0.5 to 0.66	XY:17, Z:25	0.30	2.1 - 3.0
Non-PTFE Ceramic (RO4000)	0.6 to 0.65	XY:12/16, Z:50	1.6 to 3.9	1.8 - 1.86

Table 2. Thermal management, CTE control and stiffener materials

Material	Thermal Conductivity (W/m.K)	CTE (ppm/°C)	Tensile Modulus (Msi)	Density (g/cc)
Heavy Copper	385-400	XY:17/19	12 to 16	8.90
Copper-Invar-Copper (CIC)	120-130	XY:5/6	18 to 19	9.90
Copper-Molybdenum-Copper (CMC)	180-220	XY:6/8	N/A	9.8-10
Non WOven Aramid composite	0.2-0.3	XY:9/12, Z:120	2 to 2.1	1.25-1.3
Quartz	N/A	XY:6/8, X:40	3.5 to 4.5	2.20
Copper C11000 full hard	385-400	17.00	6.40	8.90
Aluminium 5052	150	25	3.76	2.70
Aluminium 6061 T6	150	25	3.75	2.70

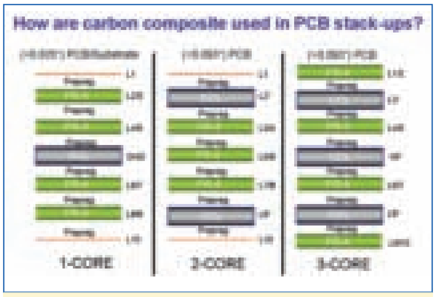

Figure 1. How carbon composites can be used in a PCB.

interconnect (HDI) PCBs with fine lines and small through holes. Essentially the PCB will be two individual PCBs with very few signals that are run through to connect the signals from each board. This design limits the engineer to design a HDI PCB with fine lines and signals and thus overall limiting the capability of the PCB.

Another example is aluminum. The material is fairly well rounded in terms of thermal, tensile modulus and density. The difficulty with this material is that it lacks CTE control, expanding at 25ppm/C. This means that there must be additional mechanical stiffeners and other solutions required to maintain the connection of the IC.

Existing exotic materials and heavy copper may even cause concern to engineers in new areas. Overall these materials are difficult to process, poor thermal conductors, require special waste treatments (for CIC & CMC), poor yields using thick metal solutions and have limitations on HDI applications.

Carbon composite laminates embedded in a PCB

The limitations of the past materials have created the need for a high performance material. Carbon composite laminates (CCL) are currently being used for a wide array of PCB solutions such-as thermal, CTE control and rigidity enhancements.

What are carbon composite laminate and their properties?

There are currently two forms of carbon fibers available in the market. The first is a low-modulus carbon fiber. The low-modulus carbon fiber has an 8 to 12 W/m.K thermal conductivity, -0.41 ppm/C CTE, tensile modulus of 30 to 35Msi and a density of 1.7-1.8g/cc. The high modulus carbon fibers have a thermal conductivity of 300 to 325W/m.K. The tensile modulus is 100 to 114Msi, which is substantially higher than low modulus carbon fiber. When the fibers are molded into a carbon composite laminate, the laminate with two sheets of copper on either side has a thermal conductivity of 75 to 175w/m.K in the X and Y direction (3 to 90W/m.K without copper sheets), a CTE of 2 to 5ppm/C, a tensile modulus of 11 to 40Msi and a density of 1.65 to 1.7g/cc. *Table 3* shows the properties of high modulus and low modulus carbon fibers and the properties of a copper clad carbon composite laminate.

Table 3. Copper Clad Carbon Composite (STABLCOR®)

Thermal, CTE control, Stiff and Light Weight Material				
E.Conductive Material	**Thermal Conductivity (W/m.K)**	**CTE (ppm/°C)**	**Tensile Modulus (Msi)**	**Density (g/cc)**
Low Modulus Carbon Fiber	8 to 12	-0.41	30 to 35	1.7-1.8
High Modulus Carbon Fiber	300-325	-1.5	100 to 114	2.1-2.2
Copper Clad Carbon Composite*	XY:75 to 175, Z:~1	2 to 5	10 to 25	1.65-1.7

* marketed as STABLCOR® Laminates

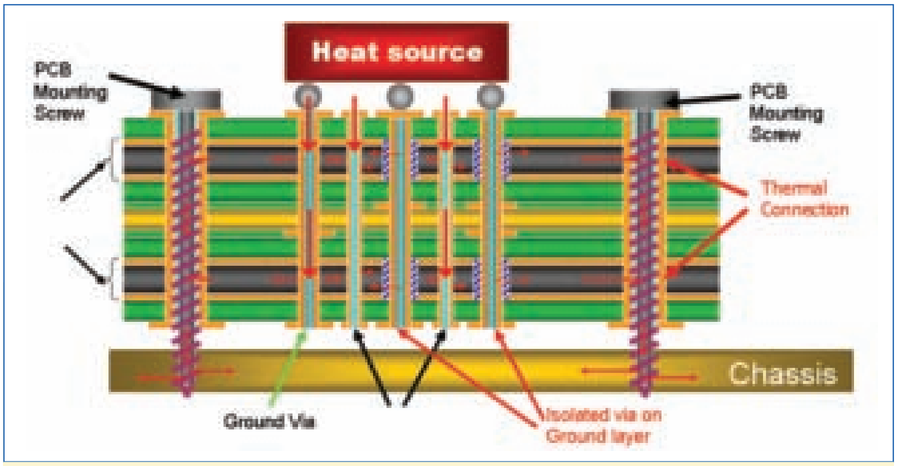

Figure 2. Carbon Composite Laminates enable heat to dissipate quickly in the X&Y plane, away from the hot spot.

How can carbon composites be used in a PCB?

Carbon composite laminates are electrically conductive, thus the laminate is used as a ground plane layer and not as a dielectric. The material can be placed in several ways in a PCB (*Figure 1*). For thinner PCB/Substrates (<0.035"), a single layer of carbon composite can be placed in the center of the PCB. For medium thickness PCBs (<0.093") a layer of CCL can be placed one layer under each surface layer. This would allow for an ideal optimization of thermal, CTE and rigidity for the PCB. For thicker PCBs, more than two CCL can be placed to enhance thermal and mechanical properties.

Benefits of carbon composite laminates

The three key enhancements of CCL to PCBs are thermal, CTE and rigidity. PCBs now can be enhanced with these three properties with almost no weight premium, making PCBs lighter, faster and stronger.

Thermal enhancement

Previously copper core or thick metal solutions were used in order to enhance the thermal properties of a PCB. The material allowed the PCB to spread heat in an isotropic manner, i.e., in a circular pattern. The difficulty with the material is that the isotropic cooling did not allow for heat to be rapidly removed away from the hot spot in the PCB; the heat simply was dissipated in a slower circular pattern.

Carbon composite laminates have in-plane (lateral) thermal conductivity, i.e., they enable heat to dissipate in the x and y plane, away from the hot spot. Heat flows from the heat-generating source through the thermal or ground copper vias to the carbon composite. Once the heat hits the carbon composites, the heat is rapidly spread throughout the PCB, in an anisotropic manner, to the edges of the board. Heat also has the ability to be dissipated through the signal vias, even though they are separated from the composite; the heat only has to pass a small distance through epoxy/polyimide barrier in order to get to the carbon. Thus the PCB acts as a heat spreader, allowing the IC to run much cooler.

Table 4. In-plane CTE of dielectric materials

DIELECTRIC MATERIAL	In Plane CTE (ppm/C)
FR-4 / E-glass	16 to 20
Polyimide/E-glass	15 to 19
Non Woven Aramid/Epoxy	9 to 12
PTFE Ceramic (RO3000)	17.00
Non-PTFE Ceramic (RO4000)	12 to 16

Table 5. Through-plane CTE of dielectric materials

DIELECTRIC MATERIAL	Through Plane CTE (ppm/C)
FR-4/E-glass	55 to 60
Polyimide/E-glass	50 to 55
Non Woven Aramid/Epoxy	110 to 120
PTFE Ceramic (RO3000)	25 to 40
Non-PTFE Ceramic (RO4000)	50 to 55

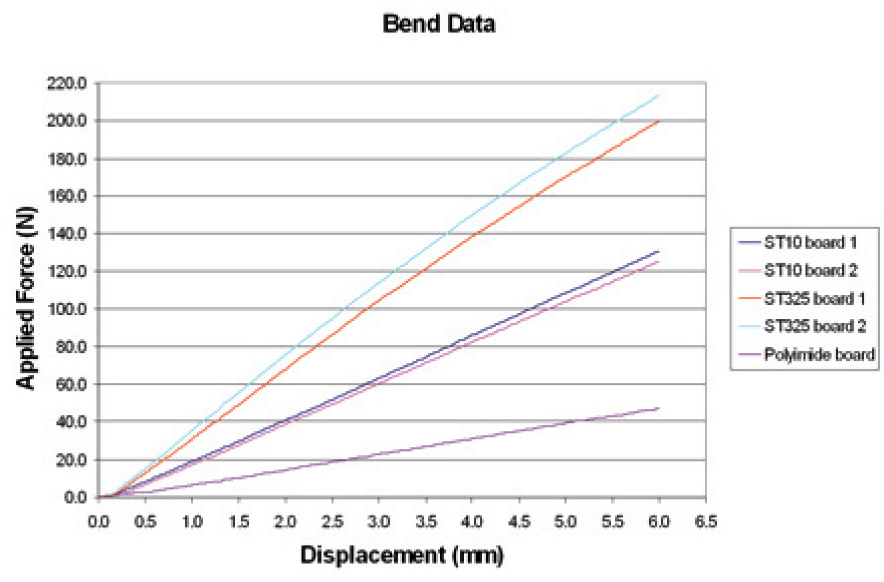

Table 5. Carbon composite materials compared to polyimide-based materials

Table 6. Results of the standard defection test

Sample Number	Sample Identification	Maximum force at 6mm (N)	Stiffness Improvement over Sample # 5
1	ST10 board 1	130.9	277.3%
2	ST10 board 2	125.4	265.7%
3	ST325 board 1	199.9	423.5%
4	ST325 board 2	213.4	452.1%
5	Polyimide board	47.2	Baseline

CTE

There are currently three types of common packaging technology in the industry: organic packages (16-19ppm/C), ceramic packages (6-8ppm/C) and DDA (direct die attach) or flip chip (2-4ppm/C). FR4 has a CTE of 17 to 19ppm/C, which works well for organic packages, but as the industry evolves the demands for low CTE packages increases, thus the need for a PCB that can tailor the CTE to match ceramic packages or even DDA/flip chip components.

In the past, non-woven aramid material (such as Kevlar) was used in order to control the CTE of the PCB. The material worked well with in-plane CTE (9 to 12ppm/C). The difficulty of the material was that it had a radical *z*-axis expansion (110 to 120ppm/C) that could cause through-hole reliability issues and be difficult to drill. The material was also moisture-absorbent and did not have much rigidity. It was discontinued as of late 2006 by the supplier.

Currently carbon composite laminates are being used in order to control the CTE of PCBs. The material has the capability to be tailored to the engineer's needs of surface CTE.

Table 7. Density comparison of laminates

Material (Laminate)	Density gm/cm3
FR4	1.80
Polyimide	1.70
Carbon Composite	**1.65**
Aluminum	2.7
Copper	8.92
CIC	9.9

Rigidity

Rigidity plays a key role in many PCBs in many aspects. The key is shock & vibration for mobile applications. Many times PCB designers use mechanical stiffeners in order to solidify the structure of the PCB. The difficulty with mechanical stiffeners is that they add a weight premium to the PCB.

Currently carbon composites enable PCBs to be much more rigid. In a standard deflection test done by independent test labs, the low modulus carbon composite was ~275% stiffer than the polyimide test sample. The high modulus carbon composite samples were ~450% stiffer than the polyimide test samples.

Density

Weight premiums are becoming a very large issue when enhancing thermal and mechanical performance of a PCB. Using many solutions to create the ideal PCB adds a fairly large weight premium. Carbon composite laminate is comparable to FR4 in density or weight.

Conclusion

In order for an engineer to find the ideal enhancing materials for a PCB, the engineer must turn to one or several solutions and may not still have the ideal solution. By using carbon composite laminates inside the PCB, an engineer can maximize the thermal, CTE and rigidity enhancements to create a more efficient printed circuit board.

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